Gradually Reconfiguring Virtual Network Topologies based on Estimated Traffic Matrices

Yuichi Ohsita, *Member, IEEE,* Takashi Miyamura, *Non-Member,* Shin'ichi Arakawa, *Member, IEEE,* Shingo Ata, *Member, IEEE,* Eiji Oki, *Senior Member, IEEE,* Kohei Shiomoto, *Member, IEEE,* and Masayuki Murata, *Member, IEEE*

***Abstract*— Traffic matrix is essential to traffic engineering (TE) methods. Because it is difficult to monitor traffic matrices directly, several methods for estimating them from link loads have been proposed. However, estimated traffic matrix includes estimation errors which degrade the performance of TE significantly. In this paper, we propose a method that reduces estimation errors while reconfiguring the VNT by cooperating with the VNT reconfiguration. In our method, the VNT reconfiguration is divided into multiple stages instead of reconfiguring the suitable VNT at once. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces the estimation errors in each stage by using information monitored in prior stages. We also investigate the effectiveness of our proposal using simulations. The results show that our method can improve the accuracy of the traffic matrix estimation and achieve an adequate VNT as is the case with the reconfiguration using the actual traffic matrices.**

I. Introduction

Network operators design their backbone networks to accommodate all traffic efficiently (e.g., without congestion or large delays). However, even if a backbone network suitable for the actual traffic is constructed, traffic could significantly differ from the initial traffic as time goes on. As a result, the previously constructed backbone network becomes no longer suitable to the current traffic; for example, it may happen that utilizations of some links are extremely high and cause congestion or large delays.

Optical layer traffic engineering (TE) [1–8] is one efficient way of accommodating traffic that changes unpredictably. Optical layer TE assumes that a network consists of IP routers and optical cross-connects (OXCs), as illustrated in Fig. 1. Each outbound port of an edge IP router is connected to an OXC port. Lightpaths (hereafter called optical layer paths) are established between two IP routers by configuring OXCs along the route between the routers. A set of optical layer paths forms a VNT (virtual network topology). Traffic between two routers is carried over the VNT using IP layer routing. In these conditions, optical layer TE accommodates time-varying traffic by dynamically reconfiguring VNTs.

Yuichi Ohsita is with Graduate School of Economics, Osaka University.

Shin'ichi Arakawa and Masayuki Murata are with Graduate School of Information Science and Technology, Osaka University.

Takashi Miyamura and Kohei Shiomoto are with NTT Service Systems Laboratories, NTT Corporation.

Shingo Ata is with Graduate School of Engineering, Osaka City University.

Eiji Oki is with Department of Information and Communication Engineering, The University of Electro-Communications.

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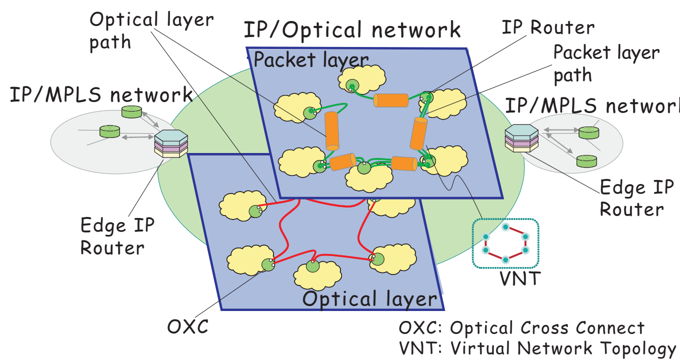


Fig. 1. IP/Optical network.

In optical layer TE, a traffic matrix, which indicates traffic volumes between all pairs of edge nodes, is required as an input. By using the traffic matrix, the VNT reconfiguration methods configure a new VNT in which constraints such as maximum utilization of optical layer paths are satisfied. One approach to obtain the traffic matrix directly is to construct fully meshed label switched paths using MPLS. However, this approach does not scale because it requires N-square number of label switched paths. Another approach is to tally the number of packets of each end-to-end traffic flow at all the edge nodes. However, this is also difficult to apply in large-scale networks, because tallying the number requires a non-negligible amount of CPU resources of edge nodes, and gathering the tallied data of all end-to-end traffic consumes a non-negligible amount of network resources such as bandwidths.

Therefore, several methods to estimate traffic matrices have been proposed [9–18]. In such methods, a whole traffic matrix is estimated by using the information (e.g., utilizations of optical layer paths) that can be collected much more easily than directly monitoring traffic matrices. However, according to Ref. [19], if we use the estimated traffic matrices as an input of a TE method, estimation errors in traffic matrices have large impacts on the performance of the TE methods and may cause the significant large utilizations of optical layer paths.

One way of handling such estimation errors is to reconfigure the VNT redundantly, taking the estimation errors into consideration. However, if the estimation errors are large, the redundant reconfiguration may require an unacceptable amount of resources such as wavelengths. To avoid the impact of estimation errors, therefore, reduction of estimation errors is necessary.

Accordingly, we newly develop a gradual reconfiguration approach that reduces the estimation errors during VNT reconfigurations. In this approach, the VNT reconfiguration is divided into multiple stages instead of reconfiguring the suitable VNT at once. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces estimation errors at each stage by using information, such as packet layer routing and utilizations of optical layer paths monitored at prior stages. By reducing the estimation errors, we can construct efficient VNTs without directly monitoring traffic matrices as is the case with the reconfiguration using the actual traffic matrices.

The rest of this paper is organized as follows. Section II summarizes related works. Then, Section III presents an overview of the gradual reconfiguration and the estimation method for the gradual reconfiguration. The detail of the estimation method for the gradual reconfiguration is explained in Sections IV. In Section V, we discuss the simulations that we used to demonstrate the limitations of the conventional method and evaluate our methods. Finally, a brief conclusion is provided in Section VI.

II. Related work

In this section, we summarize the past researches on VNT reconfiguration algorithms and traffic matrix estimation methods.

A. VNT reconfiguration method

VNT computation algorithms can be categorized as either full [1], [2] or partial reconfiguration algorithms [3–8]. In full reconfiguration, the new VNT is computed with no limitation on the number of reconfigured optical layer paths. Mukherjee *et al.* [1] formulated the full reconfiguration VNT design problems as optimization problems and proposed heuristic algorithms based on the simulated annealing approach that find nearly optimal solutions. The full reconfiguration can yield a solution that is optimal in terms of network performance such as maximum utilization of optical layer paths when using the actual traffic matrix. However, if we use the estimated traffic matrices, full reconfiguration may delete many necessary optical layer paths and add unnecessary optical layer paths due to estimation errors because full reconfiguration does not limit the number of optical layer paths to be reconfigured. Deleting necessary optical layer paths causes especially high utilization of other optical layer paths.

Therefore, in this study, we use a partial reconfiguration approach at each stage. In partial reconfiguration, the new VNT is computed with limitations on the number of reconfigured optical layer paths. By limiting the number of reconfigured optical layer paths, we can reduce the number of unnecessary additions or deletions of optical layer paths.

There are several papers proposing partial reconfiguration algorithms [3–8]. Banerjee and Mukherjee [3] present an integer linear programming (ILP) formulation for optimal VNT design. Their approach assumes that the future traffic matrix is given; the future VNT is determined by adapting the current one to accommodate the change in the traffic matrices. Gieselman *et al.* [8] proposed a heuristic reconfiguration algorithm that efficiently adapts to fluctuations in traffic. However, none of these studies consider how well the VNT reconfiguration performs under the estimated traffic matrices. In this paper, we develop an approach to reduce the estimation errors while reconfiguring the VNT in order to make the VNT reconfiguration method enable to work as expected.

B. Traffic Matrix Estimation

In the optical layer TE, information about network resources and traffic matrices are required as input. However, as described in Section I, the traffic matrices are difficult to obtain directly. Therefore, several methods to estimate traffic matrices have been proposed.

Zhang *et al.* [14] have proposed a estimation method called the tomogravity method. Tomogravity method first obtains the initial traffic matrices by using a gravity model that assumes that the amount of traffic from a source to a destination node is proportional to the total of the incoming/outgoing traffic for each edge node. Then, the method estimates the current traffic matrix by adjusting the initial traffic matrices so as to fit all the monitored link loads. Results reported by Refs. [14] and [20] show that tomogravity can follow rapid changes in amounts of traffic, and can estimate the traffic matrix on a tier-1 ISP network within 5 seconds. Recently, a method to estimate traffic matrices so as to follow the gravity model even in the case without complete observation of the edge link loads has been proposed [15].

Another type of estimation methods [10], [11] has also been proposed; they assume that edge-to-edge traffic demand follows a Gaussian distribution. Additionally, Tan *et al.* [12], [13] have proposed methods to estimate traffic matrix which fits the monitored link loads and is nearest to the initial traffic matrix obtained by assuming the Gaussian distribution.

However, the estimated traffic matrices include estimation errors due to the differences between the actual traffic and these models (i.e., gravity model or Gaussian distribution) as shown in the results described in Ref. [21]. Because these estimation errors have impacts on a TE method, we need a method that can estimate traffic matrix accurately enough for the TE method to reconfigure the suitable VNT and routes.

One approach to increase the estimation accuracy is to use additional information. Refs. [16] and [17] obtain additional information by measuring a part of end-to-end traffic. However, in a large network, we may not measure enough number of end-to-end traffic to estimate the traffic matrices accurately. Another method to obtain the additional information has been proposed by Soule *et al.* [18]. In this method, additional information is obtained by changing the routes of packet layer paths and observing the difference between utilization of links before and after routes are changed. However, this method requires changes in packet layer paths that are initially unnecessary. Also, this method does not consider how to deal with the sudden changes in traffic that cause significant estimation errors.

Our approach, in contrast, obtains additional information using the difference in utilizations of optical layer paths

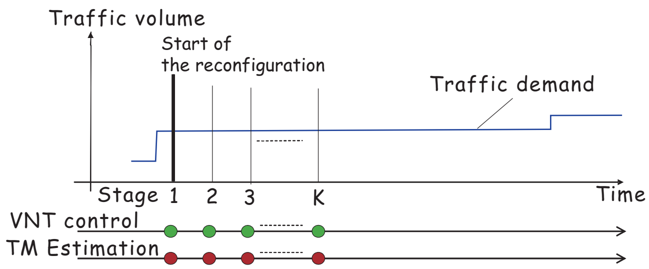


Fig. 2. Overview of gradual reconfiguration of VNT

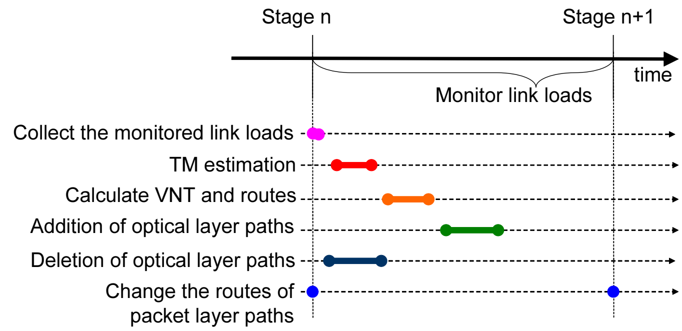


Fig. 3. Operations in each stage

caused by the VNT reconfiguration with no unnecessary route changes. Moreover, to avoid significant errors when traffic changes suddenly, our estimation method separates the information about sudden changes in traffic from the information (e.g., packet layer routing and utilization of optical layer paths) from prior stages.

III. Overview

A. Terminology

Before presenting overviews of our gradual reconfiguration approach, we explain our terminology.

Traffic matrix
: A matrix indicating the amount of traffic between all pairs of IP routers.

Physical topology
: A topology physically constructed in the optical layer that consists of OXCs and WDM optical fibers. Two OXCs are connected by a single optical fiber.

Optical layer path
: A lightpath configured between two indirectly/directly connected OXCs. An optical layer path is a set of optical fibers between the two OXCs determined by the optical layer TE. An optical layer path occupies one wavelength of each optical fiber on the route of the optical layer path.

VNT
: A topology constructed with optical layer paths. From the packet layer, an optical layer path is regarded as a single directly connected link between IP routers.

Packet layer path
: An end-to-end packet-layer traffic traversing the VNT. Packet layer paths traversing the same optical layer path share the optical layer path bandwidth.

Route of a packet layer path
: A set of optical layer paths passed by the packet layer path.

Utilization of an optical layer path
: Amount of traffic traversing the optical layer path divided by the capacity of the optical layer path.

B. Overview of gradual reconfiguration and traffic matrix estimation

Our goal is to develop a method that reduces the estimation errors while reconfiguring the VNT by cooperating with the VNT reconfiguration. To achieve this goal, we develop the gradual reconfiguration approach shown in Fig. 2. First, when the VNT reconfiguration is needed (e.g., the link utilizations exceed a threshold), we start the gradual reconfiguration. In the gradual reconfiguration, the VNT reconfiguration is divided into several stages. In each stage of the gradual reconfiguration, we assume that routes of both packet and optical layer paths are calculated by a path computation element (PCE) [22]. Then, the OXCs and the routers in the network are configured according to the calculated routes.

The operations performed in each stage are shown in Fig. 3. At the beginning of each stage, the PCE collects the monitored link loads and estimates the traffic matrix from them. Then, the PCE calculates the VNT and the routes of packet layer paths by using the estimated traffic matrix. The calculated routes are used from the beginning of the next stage.

However, in order to avoid dropping packets, the addition of optical layer paths should be done before the change of packet layer paths and the deletion of optical layer paths should be done after the change of packet layer paths. Thus, in each stage, optical layer paths not included in the VNT of the current stage are deleted after the change of routes of packet layer paths at the beginning of the current stage. Optical layer paths used at the next stage are added in advance by using the resources not used at the current stage after the calculation of the VNT for the next stage.

By iteratively performing the above operations, we reconfigure more suitable VNT as stages go on. Finally, when the goal of the reconfiguration (e.g., making the maximum link utilization less than a threshold) is achieved, the gradual reconfiguration is finished. Once the gradual reconfiguration is finished, the VNT is fixed unless another VNT reconfiguration is needed. Therefore, the performance degradations which may occur when changing the routes are only temporary.

When estimating the traffic matrix at each stage, we use the additional information obtained by monitoring the utilization of optical layer paths both before and after the VNT reconfiguration. By using the additional information, our estimation method improves the accuracy of the estimation. Then, the reconfiguration method can use more accurate traffic matrix at the next stage.

The basic idea of our gradual reconfiguration is to avoid adding or deleting many optical layer paths before the estimation errors are sufficiently reduced. Thus, any partial reconfiguration method can be applied to our gradual reconfiguration. The challenges are how to reduce the estimation errors of traffic matrices during the gradual reconfiguration. We discuss the details of our estimation method in Section IV.

IV. Traffic Matrix Estimation Method Suitable for Gradual Reconfiguration

When the VNT is reconfigured, several routes of packet layer paths are also changed. The change in routes of packet layer paths directly impacts the utilization of optical layer paths that are passed by the packet layer paths whose routes are changed. Assuming that the network is stable (i.e., the variation in traffic is small) between two continuous stages, if the measured utilization of an optical layer path is changed by VNT reconfiguration, it is safe to conclude that the difference is caused by the change in routes of packet layer paths. These differences can yield additional equations for solving the traffic matrix calculation.

Hereafter, we call our estimation method the *additional equation method*. In Subsection IV-A, we describe its basic idea. In a real network, the traffic may change from the beginning of the reconfiguration. A significant variation in traffic causes estimation error because it violates the fundamental assumption that the network is stable. To deal with obvious variations in traffic, we propose a method of eliminating the impact of the non-negligible change in traffic described in Subsection IV-B. In Subsection IV-C, we propose a method to reduce the size of the data of the previous stages in order to save the resources such as CPU and memories of a PCE.

A. Basic Idea

In our method, we use the utilization of optical layer paths monitored from the beginning of the reconfiguration. That is, to estimate the traffic matrix at stage n, we use the utilization monitored from stage 0 to stage n. In stage i, T_i, A_i, and X_i denote the actual traffic matrix, the routing matrix (i.e., the matrix in which an element corresponding to a packet layer path and an optical layer path is 1 if the packet layer path passes the optical layer path or is set to 0 if not) and the matrix indicating utilizations of optical layer paths, respectively.

Because utilization of an optical layer path is the sum of the traffic for the packet layer paths using the optical layer path, we have

$$\begin{aligned} X_i &= A_i T_i \\ &= A_i T_n + \epsilon_{i,n}, \end{aligned} \tag{1}$$

where $\epsilon_{i,n}$ denotes the change in traffic between stages i and n. At stage n, by combining all relations from X_0 to X_n, we also have

$$\begin{bmatrix} X_0 \\ \vdots \\ X_i \\ \vdots \\ X_{n-1} \\ X_n \end{bmatrix} = \begin{bmatrix} A_0 \\ \vdots \\ A_i \\ \vdots \\ A_{n-1} \\ A_n \end{bmatrix} T_n + \begin{bmatrix} \epsilon_{0,n} \\ \vdots \\ \epsilon_{i,n} \\ \vdots \\ \epsilon_{n-1,n} \\ 0 \end{bmatrix}. \tag{2}$$

According to Ref. [23], backbone IP traffic is stationary with a period of 1 to 1.5 hours. Thus, unless the gradual reconfiguration takes more than 1.5 hours, $\epsilon_{i,n}$ is considered to be small.

To estimate the traffic matrix $\hat{T}_n$ from Eq. (2), we apply the pseudo-inverse calculation method described in [24]. The traffic matrix $\hat{T}_n$ is obtained from

$$\hat{T}_n = \bar{A}_n^{+} \bar{X}_n, \tag{3}$$

where $\bar{A}_n^{+}$ is the pseudo-inverse of matrix $\bar{A}_n$, and $\bar{A}_n$ and $\bar{X}_n$ are the matrices defined as,

$$\bar{X}_n = \begin{bmatrix} X_0 \\ \vdots \\ X_i \\ \vdots \\ X_n \end{bmatrix} \tag{4}$$

and

$$\bar{A}_n = \begin{bmatrix} A_0 \\ \vdots \\ A_i \\ \vdots \\ A_n \end{bmatrix}. \tag{5}$$

A pseudo-inverse matrix is a generalized inverse matrix and by using pseudo-inverse matrix, Eq. (3) can estimate $\hat{T}_n$ so as to minimize the squared sum of $\epsilon_{i,n} (0 \leq i \leq n)$. We calculate the pseudo-inverse matrix by using the Singular Value Decomposition (SVD) method [24]. In this method, when $k > l$, the $k \times l$ sized matrix, $\bar{A}$ is decomposed as

$$\bar{A} = U \Sigma V^T, \tag{6}$$

where U is the $k \times k$ sized matrix, V is the $l \times l$ sized matrix,

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_l \\ 0 & 0 & \cdots & 0 \end{bmatrix}, \tag{7}$$

and the $\{\sigma_i\}$ are the singular values of the matrix $\bar{A}$. Then, $\bar{A}^+$ is calculated by

$$\bar{A}^+ = V \Sigma^+ U^T, \tag{8}$$

where

$$\Sigma^+ = \begin{bmatrix} \frac{1}{\sigma_1} & 0 & \cdots & 0 & 0 \\ 0 & \frac{1}{\sigma_2} & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \frac{1}{\sigma_l} & 0 \end{bmatrix}. \tag{9}$$

However, if we simply apply the pseudo-inverse of $\bar{A}_n$ to solve Eq. (3), some elements in $\hat{T}_n$ may have negative values, which are nonexistent as regards the traffic matrix. The following iteration eliminates such negative values. We define the estimated traffic matrix for the i-th iteration as $\hat{T}_n^{(i)}$.

Step 1 Let $\hat{T}_n^{(0)} \leftarrow \hat{T}_n$

Step 2 Calculate $\hat{T}_n^{(i)}$ from $\hat{T}_n^{(i-1)}$ by using

$$\hat{T}_n^{(i)} = \hat{T}_n^{(i-1)} + \bar{A}_n^{+}(\bar{X}_n - \bar{A}_n \hat{T}_n^{\prime(i-1)}), \tag{10}$$

where $\hat{T}_n^{\prime(i)}$ is a matrix in which we replace all negative values of $\hat{T}_n^{(i)}$ with zero.

Step 3 If all elements in $\hat{T}_n^{(i)}$ are non-negative values, go to *Step 4*, or else back to *Step 2*.

Step 4 Let $\hat{T}_n^{(i)}$ be the final result of traffic matrix $\hat{T}_n$

In the additional equation method, the accuracy of the estimation is never degraded in each stage because the estimated traffic matrices are estimated so as to fit not only the currently obtained additional information but also all the information used by the estimation of the previous stage. Since the improvement of the accuracy continues until the gradual reconfiguration is finished, reconfiguration methods can achieve their goals at the end.

Among the steps to estimate the traffic matrix, the SVD takes the most of the calculation time. According to Ref. [25], the calculation time of the SVD is $O(kl^2)$ when the size of the matrix is $k \times l$ and $k \gg l$. In our case, the size of $\bar{A}_n$ is $Ln \times M^2$ at stage n, where M is the number of nodes and L is the number of optical layer paths. Thus, if $Ln > M$, we can assign Ln to k and M^2 to l, and the calculation time of the basic idea of our method is $O(LnM^4)$ at stage n.

This estimation process does not take too long time. In our evaluation described in Section V, the estimation process of the basic idea takes only 1.3 seconds for the 19 node topology at stage 15 by using the ordinary PC with 3.20 GHz Intel Pentium D Processor and 2 GB RAM.

B. Dealing with non-negligible changes in traffic

The basic idea described above assumes that the network is stable (i.e., the variation in traffic is small). However, in real networks, the traffic may change from the beginning of the reconfiguration. Significant variation in traffic causes estimation error because it violates the fundamental assumption of the additional equation method.

Therefore, we remove the information about non-negligible change in traffic from the information monitored at previous stages in order to avoid violating the assumption. Our proposed estimation method contains the following steps.

Step 1 Identify the packet layer paths including non-negligible changes

Step 2 Remove the information about the traffic of the identified paths from the information monitored at previous stages

Step 3 Estimate the traffic matrix by using the information in which information about the traffic of the identified paths is removed

In the rest of this subsection, we describe these steps in detail.

1) Identify the packet layer paths, including non-negligible change: First, we identify the packet layer paths including non-negligible changes. To do this, we use the method proposed in Ref. [26], which identifies source nodes of DDoS attacks based on increase in utilization. We identify the packet layer paths including non-negligible changes in stage n as follows.

First, we calculate differences D_n between the utilization monitored at stage n and the utilization forecasted using the estimated traffic matrix from stage $n-1$.

$$D_n = X_n - A_n \hat{T}_{n-1} \tag{11}$$

Then, we estimate matrix G_n indicating the increases in traffic flows between all pairs of edge nodes using D_n. Finally, if there are elements in G_n that are larger than a threshold Γ, we identify the packet layer paths that correspond to the elements as the paths that include non-negligible changes.

Though this step requires estimation of G_n, we do not have to estimate it accurately. The aim of this step is to identify packet layer paths that include traffic flows increasing significantly more than others. Therefore, when estimating G_n, we have only to estimate the elements corresponding to the packet layer paths with significantly increasing traffic as large values. In this study, we used the tomogravity method to estimate G_n from D_n. In the tomogravity method, the elements of G_n are estimated as the value proportional to the increase of incoming/outgoing traffic for each edge node. Because elements in D_n corresponding to the incoming/outgoing traffic for the source and destination nodes of the packet layer paths with significantly increasing traffic are large, the tomogravity method can estimate the elements in G_n that correspond to the packet layer paths with significantly increasing traffic as large values.

2) Removal of information about non-negligible changes: We remove the information about packet layer paths with non-negligible changes from the information monitored in the previous stages as follows.

We first remove the information of the identified packet layer paths from the routing matrices A_i by replacing the elements corresponding to the identified paths by 0. We denote the routing matrix after the replacement as A_i', in which the element corresponding to the packet layer path from n to m and the optical layer path between k and l is given by

$$a_i^{\prime n,m,k,l} = \begin{cases} 0, & \text{if traffic from } n \text{ to } m \\ & \text{changes significantly} \\ a_i^{n,m,k,l}, & \text{otherwise} \end{cases}, \tag{12}$$

where $a_i^{n,m,k,l}$ is the element of A_i indicating whether or not the packet layer path from n to m passes the optical layer path between k and l.

Then, we create the utilization matrix X_i' in which the information about the identified packet layer paths are removed, which is given by

$$X_i' = X_i - (A_i - A_i')\hat{T}_{n-1}. \tag{13}$$

In this equation, $(A_i - A_i')\hat{T}_{n-1}$ indicates the matrix of the identified traffic on each link caluclated by using the traffic matrix estimated at stage $n-1$.

3) Estimate the traffic matrix: To estimate the traffic matrix, we use the equation,

$$X_i' = A_i' T_n + \epsilon_{i,n} \tag{14}$$

instead of Eq. (1). Similar to Eq. (2), by combining all relations from X_0 to X_n, we also have

$$\begin{bmatrix} X'_0 \\ \vdots \\ X'_i \\ \vdots \\ X'_{n-1} \\ X_n \end{bmatrix} = \begin{bmatrix} A'_0 \\ \vdots \\ A'_i \\ \vdots \\ A'_{n-1} \\ A_n \end{bmatrix} T_n + \begin{bmatrix} \epsilon_{0,n} \\ \vdots \\ \epsilon_{i,n} \\ \vdots \\ \epsilon_{n-1,n} \\ 0 \end{bmatrix}. \quad (15)$$

Because we remove the information about the traffic with non-negligible changes, X'_i does not include the information about the traffic with non-negligible changes. That is, $\epsilon_{i,n}$ is small. Therefore, as in Eq. (3), we can estimate $\hat{T}_n$ as

$$\hat{T}_n = \bar{A'}_n^+ \bar{X'}_n, \quad (16)$$

where $\bar{A'}_n^+$ is the pseudo-inverse of the matrix $\bar{A'}_n$, and $\bar{A'}_n$ and $\bar{X'}_n$ are the matrices defined as

$$\bar{X'}_n = \begin{bmatrix} X'_0 \\ \vdots \\ X'_i \\ \vdots \\ X'_n \end{bmatrix} \quad (17)$$

and

$$\bar{A'}_n = \begin{bmatrix} A'_0 \\ \vdots \\ A'_i \\ \vdots \\ A'_n \end{bmatrix}. \quad (18)$$

C. Reduction of the size of matrix

Partial reconfiguration changes only a small number of paths at each stage. That is, most elements of $\Delta A'_i = A'_i - A'_{i-1}$ are expected to be 0. Thus, we introduce following procedure that reduces the size of the matrix.

First, we transform X'_i and A'_i into the matrices, $\Delta X'_i = X'_i - X'_{i-1}$ and $\Delta A'_i = A'_i - A'_{i-1}$. Second, we remove rows $\Delta {a_i'}^{(j)}$ in $\Delta A'_i$ if $\Delta {a_j'}^{(j)}$ = O. We also remove the same position of the row $\Delta {x_i'}^{(j)}$ in ΔX_i. We denote $\Delta X'_i$ and $\Delta A'_i$ after row removals as $\Delta X''_i$ and A''_i respectively. Finally, we use

$$\hat{T}_n = \Delta \bar{A''}_n{}^+ \Delta \bar{X''}_n, \quad (19)$$

where $\Delta \bar{A''}_n{}^+$ is the pseudo-inverse of the matrix $\Delta \bar{A''}_n$, and $\Delta \bar{A''}_n$ and $\Delta \bar{X''}_n$ are the matrices defined as

$$\Delta \bar{X''}_n = \begin{bmatrix} \Delta X''_1 \\ \vdots \\ \Delta X''_i \\ \vdots \\ \Delta X''_n \\ X'_n \end{bmatrix} \quad (20)$$

and

$$\Delta \bar{A''}_n = \begin{bmatrix} \Delta A''_1 \\ \vdots \\ \Delta A''_i \\ \vdots \\ \Delta A''_n \\ A'_n \end{bmatrix}. \quad (21)$$

instead of Eq. (16)

The size of the matrix $\Delta \bar{A''}_n$ is $(L + L'n) \times M^2$, where L' is the number of optical layer paths related to the changes of packet layer paths at each stage. The size of $\Delta \bar{A''}_n$ is much smaller than the size of $\bar{A}_n$, since partial reconfiguration changes only a small number of paths at each stage. Thus, by using $\Delta \bar{A''}_n$ instead of $\bar{A}_n$, we can speed up the estimation process of the additional equation method.

Moreover, we can dramatically reduce the calculation time of each stage by the estimation method adjusting the traffic matrices estimated at the previous stage by using the additional information obtained at the current stage, which is one of our future research topics. By applying this, we can significantly reduce the sizes of matrices whose pseudo-inverse matrices need to be calculated at each stage, and can estimate traffic matrices in minutes even if the number of nodes is more than 200.

V. Evaluation

In this section, we describe the simulation conditions, explain how the simulations demonstrate the effectiveness of the gradual reconfiguration method with the existing traffic matrix estimation, and evaluate the gradual reconfiguration method using the additional equation method.

A. The partial reconfiguration method

Our gradual reconfiguraiton can use any partial reconfiguration method at each stage. In this evaluation, we use a heuristic method proposed in Ref. [8]. This method adds a new optical layer path to mitigate congestion and, if possible, deletes a currently underutilized optical layer path for reclamation. This method allows only one optical layer path to be added or deleted in each stage. However, in our method, the number of optical layer paths added or deleted at each stage may affect the number of additional equations and the estimation errors. We therefore extend the reconfiguration methods in Ref. [8] such that it can add or delete multiple optical layer paths at each stage. N denotes the maximum number of paths to be added or deleted. We set $N = \infty$ to obtain results for the full reconfigurations.

The extended method uses two thresholds for the utilization of each optical layer path to define the *congested* and *underutilized* states. T_H and T_L denote thresholds for *congested* and *underutilized*, respectively. In our evaluations, we set T_L to 0.5 times T_H. The general sequence of the algorithm to calculate the VNT at each stage is as follows:

Step 1 Check the utilization of all optical layer paths. If at least one congested optical layer path (i.e., a path whose utilization exceeds the threshold T_H) is found, go to the optical layer path addition phase (Step 2). If there is an optical layer path whose utilization is less than threshold T_L, go to *Step 3*

Step 2 Execute the *optical layer path addition phase* described below, and then go to *Step 4*.

Step 3 Execute the *optical layer path deletion phase* described below, and then go to *Step 4*.

Step 4 Calculate the routes of packet layer paths over the new VNT and obtain the expected utilization of all optical layer paths of the new VNT.

Step 5 Decrement the number of optical layer paths to be added/deleted in this stage, i.e., $N = N - 1$. If $N = 0$, go to *End*. Otherwise, go back to *Step 1*.

End

Finally, when utilizations of all optical layer paths become less than T_H and any optical layer paths cannot be deleted, the gradual reconfiguration finishes.

In the above steps, the routes of packet layer paths over the VNT are calculated so as to make the maximum link utilizations less than $T_H - \eta$, where η indicates the margin for the fluctuations of traffic. In our evaluations, we set η to $0.1 \times T_H$. The calculation of the routes of packet layer paths is performed as follows. 1) When utilizations of all optical layer paths on the route of a packet layer path in the previous stage are lower than $T_H - \eta$, the route is kept in the current stage because there is no need to change it. 2) Otherwise, the route is calculated using constraint-based shortest path first (CSPF) [27] so as to limit maximum utilizations to less than $T_H - \eta$.

The details of optical layer path addition/deletion phases are as follows.

1) *Optical layer path addition phase:*
If the utilization of an optical layer path exceeds T_H, a new optical layer path is set up to reroute traffic away from the *congested* optical layer path. First, we collect a set of packet layer paths that pass the most congested optical layer path. Then, we select the busiest of the collected packet layer paths. Finally, we add the direct optical layer path (i.e., a single directly connected link) from ingress to egress nodes of the selected packet layer path.

2) *Optical layer path deletion phase:*
If the utilization of an optical layer path is less than T_L and the deletion of the optical layer path is shown not to cause congestion, the path is torn down so the IP router ports and wavelengths can be reclaimed for future use. The optical layer path is checked for potential for its deletion to cause congestion by calculating the utilization of optical layer paths after deletion using the traffic matrix estimated in the current stage. If there is more than one candidate for deletion, each candidate path is tested in ascending order of utilization.

In our evaluations, we implement the above algorithm by using C++.

B. Simulation Conditions

In our simulation, we use the European Optical Network (EON) (19 nodes, 37 links) shown in Fig. 4 as the physical topology. In this figure, circles represent OXCs, and lines represent optical fibers. The number of wavelengths for each optical fiber is set to 16.

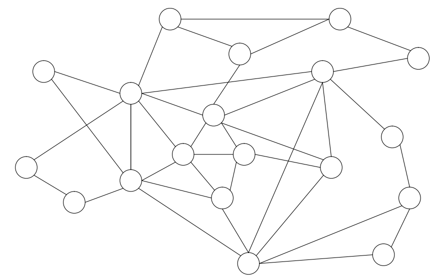


Fig. 4. EON topology

In our simulation, we implement estimation methods by using MATLAB and the ordinary PC with 3.20 GHz Intel Pentium D Processor and 2 GB RAM. In the additional equation method, we use a parameter, Γ which indicates sensitivity for detection of change in traffic; the traffic whose increase is larger than Γ is identified as traffic including non-negligible changes, and the previously monitored information about the traffic is not used for estimating traffic matrix. If we set Γ to too large a value, there is still a non-negligible change in traffic in the information used by the additional equation method. This causes estimation errors. However, a too small Γ causes misdetection of traffic with no non-negligible changes (false positives). As a result, the additional equation method cannot use many of the utilizations monitored in the previous stages. Therefore, we should set the Γ to as small a value as possible such that it will not detect traffic with no non-negligible change by monitoring the traffic in advance. In our simulations, Γ is set to $0.2 \times T_H$ times of the bandwidth of an optical layer path.

In this environment, at Stage 15, the estimation process of our basic idea described in Subsection IV-A takes 1.3 seconds and the estimation method using $\Delta\bar{A}''$ described in Subsection IV-C takes 0.8 seconds by using the ordinary PC with 3.20 GHz Intel Pentium D Processor and 2 GB RAM. In the rest of this section, we show only the results for the method using $\Delta\bar{A}''$ since the estimation results by the basic idea are similar.

In our evaluations, we generate the initial traffic matrix where the elements of it follow the lognormal distribution [23]. We set the parameters of lognormal distribution to be the same in Ref. [23], and scale each element such that its average is $0.3 \times T_H$. The initial VNT is configured using the initial traffic matrix by the VNT reconfiguration method described in Subsection V-A with $N = \infty$. The changes are randomly generated within the range from -0.4 to 0.4 times the elements of the initial traffic matrix, based on the observation that, in the Abilene [28], the amount of traffic increases about 1.4 times in 2 hours when the daily change of the traffic is the largest.

C. The case without change of traffic

In this subsection, to focus on the impact of estimation errors, we simulate the ideal case that the traffic is constant in all stages.

1) Improvement of accuracy of the estimation: First, we compare the accuracy of our estimation method with the tomogravity method [14] where N is set to 1, 3, and 5. We conducted the simulations using ten different traffic matrices, and the averaged results are presented in following figures.

To compare the accuracy of the estimated traffic matrices, we use the root mean squared relative error (RMSRE) as follows,

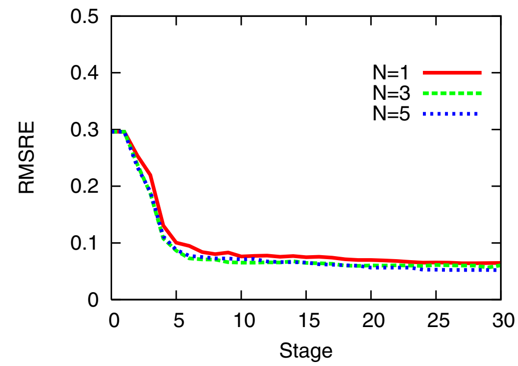
$$\text{RMSRE} = \sqrt{\frac{1}{N_{\tilde{t}}^2} \sum_{1 \leq i,j \leq N, t_{i,j} > \tilde{t}} \left(\frac{\hat{t}_{i,j}(n) - t_{i,j}(n)}{t_{i,j}(n)} \right)^2} \quad (22)$$

where $\hat{t}_{i,j}$ and $t_{i,j}$ are the estimated and actual amount of traffic from i to j, respectively. The RMSRE gives a relative measure. However, the relative errors of small matrix elements affect RMSREs, though they are not really important. Thus, in computing the RMSRE, we consider only matrix elements greater than a threshold $\tilde{t}$. $N_{\tilde{t}}$ is the number of elements greater than $\tilde{t}$ in a traffic matrix. In the following simulations, $\tilde{t}$ was set so that the sum of the end-to-end traffic whose actual rate was greater than $\tilde{t}$ composed 75 % of the total traffic. In our case, about a half of the all end-to-end traffic occupies 75 % of the total traffic. That is, a half of the all end-to-end traffic is pruned in the estimation results shown in this section. However, we verified that the results of the mean squared errors calculated for all the end-to-end traffic are similar.

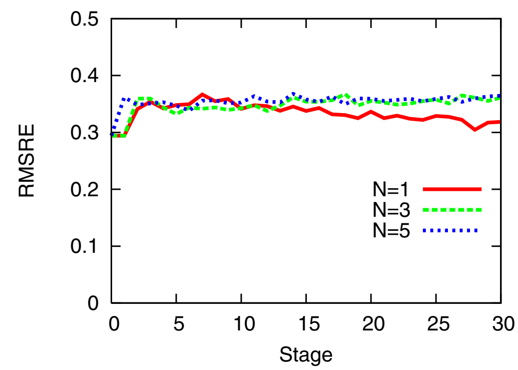
Figure 5 shows the RMSREs for each stage. In these graphs, the horizontal axis represents the number of stages after the beginning of the VNT reconfiguration, and the vertical axis represents the RMSREs. As can be seen in this figure, the additional equation method reduces estimation errors as the stages are completed, while estimation errors of the tomogravity method are large in all stages. This is caused by the difference in the number of equations used in traffic matrix calculation. The tomogravity method uses only the utilizations monitored at each stage. That is, the tomogravity method uses only the same number of equations as the number of optical layer paths. On the other hand, when some routes of packet layer paths are changed, the additional equation method adds the equations about the packet layer paths whose routes are changed. As a result, the number of equations used by the additional equation method increases as it progresses through the stages.

If there are few changes in the routes of packet layer paths, the additional equation method cannot increase the accuracy of the estimation. However, in such cases, the current VNT and routes satisfy the objective of the TE method and the reconfiguration is not required, which is the reason why the routes do not change. Thus, the current VNT and routes are fixed unless another reconfiguration becomes necessary due to changes of traffic and so on. Therefore, we do not need to increase the accuracy of the estimation in such cases since the current traffic matrix is not required by the TE method.

Figure 5 also shows that the estimation errors are reduced to the same level regardless of N at each stage. This is because the number of packet layer paths whose routes are changed are almost the same regardless of N. In this simulation, a packet layer path is routed on the VNT according to the following



(a) Additional equation method



(b) Tomogravity

Fig. 5. RMSREs

policy; when a packet layer path can be accommodated to the same route as the previous stages without causing utilizations higher than $T_H - \eta$, the packet layer path is accommodated on the same route as the previous stage, otherwise the routes are re-calculated using CSPF so as to limit the maximum link utilization to less than $T_H - \eta$. When one or more optical layer paths are added, the packet layer path traversing the optical layer paths whose utilizations are higher than $T_H - \eta$ moves to the optical layer paths whose utilizations are low. Because the number of packet layer paths traversing optical layer paths whose utilizations are higher than $T_H - \eta$ before the VNT reconfiguration is the same regardless of N, the number of packet layer paths whose routes are changed is also almost the same regardless of N.

2) Effectiveness of gradual reconfiguration: In this paragraph, we investigate the VNT reconfigured by our gradual reconfiguration. First, we compare the following four methods.

- Gradual reconfiguration using the additional equation method
- Gradual reconfiguration using the tomogravity method
- Full reconfiguration using the traffic matrix estimated by tomogravity method.
- Full reconfiguration using the actual traffic matrix (i.e., ideal case)

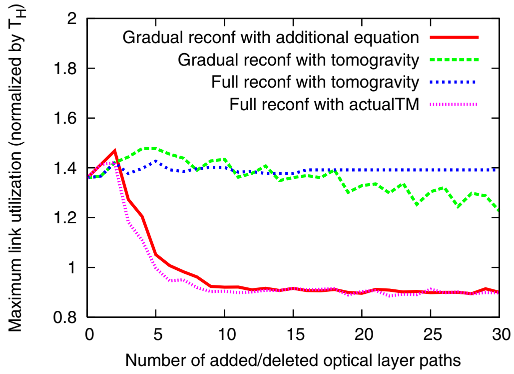


Fig. 6. Number of added/deleted paths vs maximum utilization

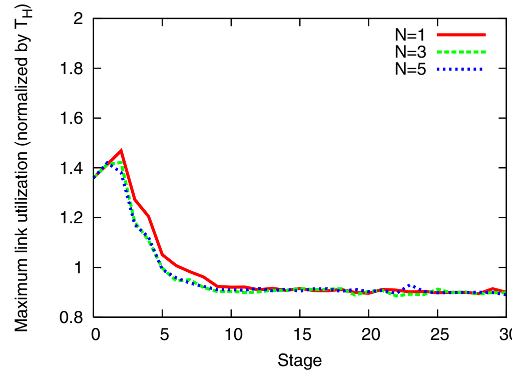


Fig. 7. Maximum utilization (with various N)

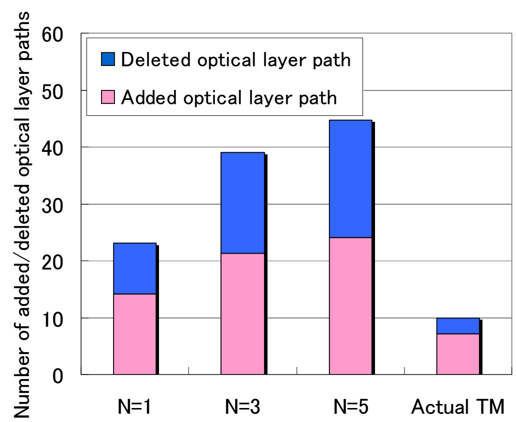


Fig. 8. Number of added/deleted optical layer paths of additional equation method

Figure 6 compares the maximum utilization when optical layer paths of the same number are added or deleted. In this figure, the horizontal axis represents the number of added or deleted optical layer paths and the vertical axis represents maximum utilization normalized by the threshold T_H. We set N to 1 for the gradual reconfigurations.

From this figure, full reconfiguration using the traffic matrix estimated by tomogravity method can never make the link utilization less than T_H. This is because the full reconfiguration decides whether additional optical layer paths are needed based on utilization calculated using the traffic matrix estimated at the beginning of the VNT reconfiguration. Therefore, the optical layer path whose actual utilization is more than T_H is mistakenly identified as a path whose utilization is less than T_H. As a result, though the maximum utilization is still over the threshold, the VNT reconfiguration is completed.

In the gradual reconfiguration, because we re-estimate traffic matrix based on the monitored link loads at each stage, the VNT reconfiguration is never completed until the maximum link utilization becomes less than T_H. However, the gradual reconfiguration using the tomogravity method cannot make the maximum utilization less than T_H due to estimation errors of the tomogravity.

On the other hand, similarly to the case using the actual traffic matrices, the gradual reconfiguration using the traffic matrix estimated by the additional equation method can reconfigure an adequate VNT whose maximum utilization is under T_H. This is because the additional equation method can reduce the estimation errors as it progresses through the stages. In the gradual reconfiguration, if the TE method cannot reconfigure the sufficient VNT due to estimation errors, the VNT is reconfigured again at the next stage and the results of the reconfigurations are used as the additional information. Thus, the increase of the accuracy of the additional equation method continues regardless of the topology, until the VNT and routes satisfy the objective of the TE method and become fixed.

Next, we investigate the impact of parameter N on the gradual reconfiguration using the additional equation method. Figure 7 compares the maximum utilization normalized by T_H in the case of setting N to 1, 3 and 5. From this figure, regardless to N, we can reduce the maximum utilization as stages go on. In each stage, though the maximum link utilization of the case of $N = 3$ or $N = 5$ is slightly less than that of the case of $N = 1$, the difference is only small. This is because at the early stages before the estimation errors are not reduced enough, we cannot set the VNT suitable to the current traffic due to estimation errors. As a result, we cannot reduce link utilizations as much as expected even when adding more optical layer paths.

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Figure 8 shows the number of optical layer paths added or deleted by the gradual reconfiguration using the additional equation method until the VNT becomes stable. In this figure, we compare the cases where $N = 1$, 3, and 5. In this figure, if we set N to a smaller value, we can reconfigure the adequate VNT by adding or deleting a small number of optical layer paths. Especially, if we set N to 1, the number of added or deleted optical layer paths is significantly smaller than the cases of $N = 3$ and $N = 5$ though the number is larger than the case using the actual traffic matrices. This is because many optical layer paths are added or deleted before the estimation errors are reduced when there is a large N. As a result, due to estimation errors, many unnecessary optical layer paths are added.

According to the above results in this subsection, the gradual reconfiguration can reduce the estimation errors dramatically even when we allow only one optical layer path to be added or deleted in each stage. In addition, by using the traffic matrices whose accuracies are improved at each stage, the gradual reconfiguration can achieve the adequate VNT as is the

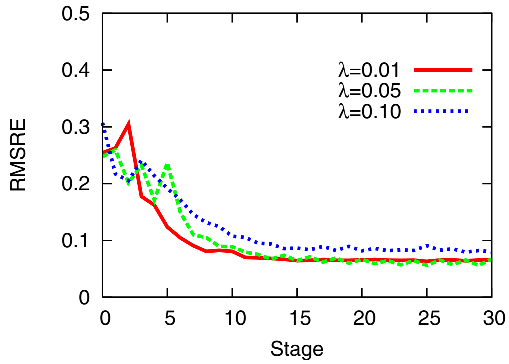

Fig. 9. RMSREs of additional equation method (the case with changes of traffic)

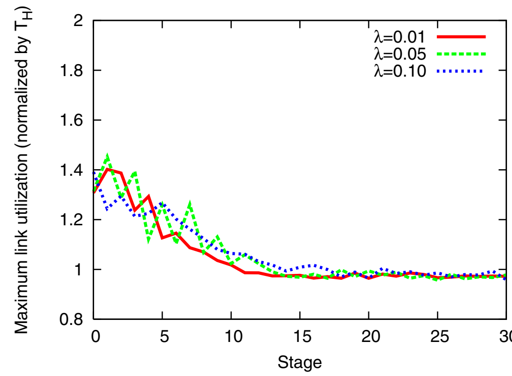

Fig. 10. Maximum utilization (the case with changes of traffic)

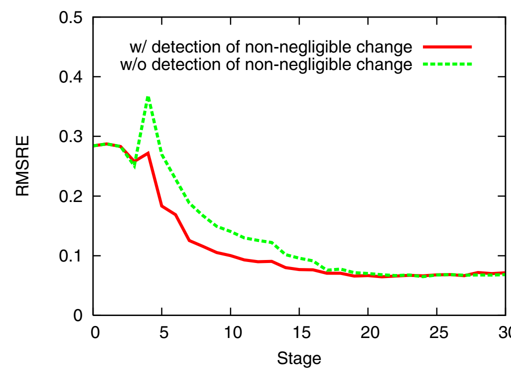

Fig. 11. Estimation errors when there is a sudden change in traffic

case with the reconfiguration using the actual traffic matrices. Especially, by imiting the number of added or deleted optical layer paths at each stage, we can achieve the adequate VNT by adding or deleting a small number of optical layer paths.

D. The case that traffic changes

The evaluation described above assumes that the traffic is constant after the beginning of the VNT reconfiguration. However, real traffic changes over time. Therefore, in this subsection, we evaluate our methods in the case that traffic changes.

1) Adaptability to the fluctuations in traffic: According to the dynamic stationary model proposed in Ref. [23] which models traffic fluctuations with a period of 1 to 1.5 hours, we generate changes in traffic as follows.

$$t_{i,j,n} = \alpha_{i,j} + \gamma_{i,j,n} \tag{23}$$

where $t_{i,j,n}$ is the amount of traffic from node i to node j at stage n, $\alpha_{i,j}$ is the average of traffic from node i to node j, and $\gamma_{i,j,n}$ is the factor by which traffic fluctuates. In this simulation, we generated the value of $\gamma_{i,j,n}$ based on Gaussian random values whose average is 0 and variance is $(\lambda\alpha_{i,j})^2$. Then, by changing the value of λ, we changed the size of the fluctuation in traffic.

Figure 9 shows the results for $\lambda = 0.01$, 0.05, and 0.10. In this simulation, we set N to 1. We set $\alpha_{i,j}$ equal to the element of the matrix used in the previous paragraph. Similar to the previous paragraph, we simulated our gradual reconfiguration ten times by using different traffic matrices and Fig. 9 shows the averages of results.

In this graph, the horizontal axis represents number of stages from the beginning of the VNT reconfiguration, and the vertical axis represents the RMSREs. From this figure, the smaller λ is, the faster we can reduce the estimation errors. However, even when $\lambda = 0.10$, the additional equation method can reduce estimation errors significantly, because in this method, the number of equations used to estimate the traffic matrix increases as it progresses through the stages. The additional equations constrain the solution of the traffic matrix estimation. Because we generated the fluctuation component of traffic according to Gaussian random values whose average is 0, no utilization monitored in any stage is far from the traffic in the current stage. In addition, the utilizations monitored in stages with temporally high or low traffic are balanced out. As a result, since the constraints from the additional equations are appropriate to the current traffic, we can increase the accuracy of the traffic matrix estimation as we progress through the stages.

Figure 10 shows the maximum link utilizations in each stage. Since the accuracy of the estimated traffic matrix is dramatically improved as stages go on, the gradual reconfiguration can make the maximum link utilizations less than T_H after several stages from the beginning of the reconfiguration as is the case with the previous subsection. That is, the gradual reconfiguration can efficiently work even in the case traffic fluctuates.

2) Adaptability to sudden change in traffic: There is another type of change of traffic. According to the results described in Ref. [29], some end-to-end traffic may change suddenly. We evaluated our additional equation method when such sudden changes in traffic occur during the gradual reconfiguration. In this simulation, we generated sudden changes in traffic by doubling five randomly selected elements in the traffic matrix described in the previous paragraph. We set λ to 0.05 and N to 1 and added a sudden change in Stage 4.

Figure 11 compares estimation errors for the additional equation method with and without detection of non-negligible change. In this figure, the horizontal axis represents stages since the beginning of the VNT reconfiguration and the vertical axis represents the RMSREs. From this figure, at Stage 4, the estimation errors of the additional equation method without detection of non-negligible change increase significantly. This

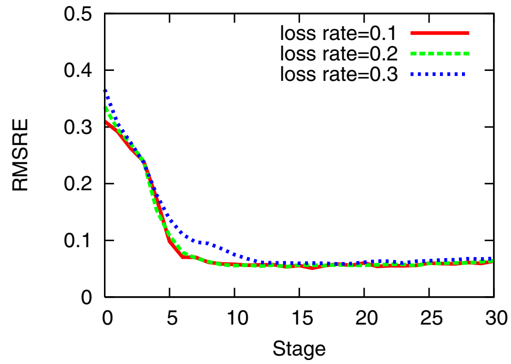

Fig. 12. RMSREs in the case of the loss of the link load information

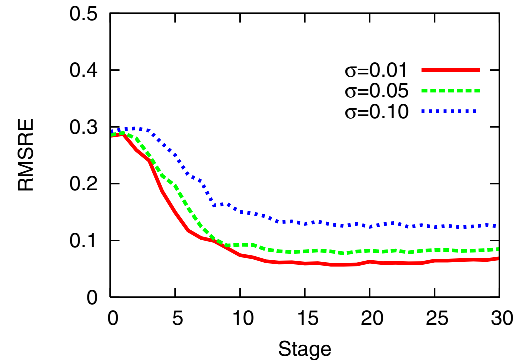

Fig. 13. RMSREs in the case of the inaccurate link load information

is because the utilization before the sudden change, which is far from the current traffic, is used to estimate the traffic matrix. On the other hand, the additional equation method with detection of non-negligible change can reduce the estimation errors even after Stage 4 because it can remove the information about the traffic with non-negligible change. That is, even when there is a sudden change in traffic, by identifying and deleting the information about the traffic with such changes, the additional equation method can estimate a traffic matrix accurately. As a result, an accurate traffic matrix is available for VNT reconfiguration.

E. *The case that monitoring link loads is less reliable*

Finally, we investigate the robustness of the additional equation method to the loss or inaccuracy of the monitored link loads.

1) Robustness to the loss of the link load information: Typical methods to collect link loads (e.g., SNMP) use UDP transport. Thus, some of the link loads may not be collected due to the packet loss. In this paragraph, we discuss how the additional equation method works in the case of the loss of the link load information.

Figure 12 shows the RMSREs for each stage when the loss rates of the link load information are 0.1, 0.2 and 0.3. In this simulation, we used the same traffic matrices in the case of $\lambda = 0.05$ used in Subsection V-D.1. Similar to the above results, this figure shows the averages of the results using ten different traffic matrices.

From this figure, even when the loss rate is 0.3, we can reduce the RMSREs dramatically. This is because we can obtain the additional information from the collected link loads even if some of link loads cannot be monitored, though the loss of the information reduces the number of additional information.

2) Robustness to the inaccurate link load information: Monitored link loads may include monitoring errors. That is, monitored link load matrix $\hat{X}_i$ is described by

$$\hat{X}_i = X_i + e_i \tag{24}$$

where X_i denotes the actual link loads and e_i denotes monitoring errors. In this paragraph, we evaluate the gradual reconfiguration with the additional equation method when the link load information is inaccurate. In this evaluation, we generated e_i based on Gaussian random values whose average is 0 and variance is $(\sigma X_i)^2$. We used the same actual traffic matrices in the case of $\lambda = 0.05$ used in the previous paragraph.

Figure 13 shows RMSREs in the cases of $\sigma = 0.01$, $\sigma = 0.05$ and $\sigma = 0.10$. We conducted the simulations using ten different traffic matrices and this figure shows the averages of the results. From this figure, the RMSREs are dramatically reduced even in the case of $\sigma = 0.10$, though the reduction is smaller than the case of smaller σ. This is because the monitoring errors whose corresponding elements of e_i are positive or negative are balanced out, similar to the case of the fluctuations of traffic described in Subsection V-D.1.

VI. Concluding Remarks

We have proposed a method that reduces estimation errors during VNT reconfiguration by cooperating with the VNT reconfiguration. Our method reconfigures the VNT gradually by dividing it into multiple stages. By dividing the VNT reconfiguration into multiple stages, our traffic matrix estimation method calibrates and reduces the estimation errors in each stage by using information monitored in prior stages. We have also investigated the effectiveness of our proposal using simulations. The results show that our method can improve the accuracy of the traffic matrix estimation and achieve an adequate VNT as is the case with the reconfiguration using the actual traffic matrices.

One of our future research topics is to speed up our estimation method. One method to speed up our estimation method is to adjust the traffic matrices estimated at the previous stage by using the additional information obtained at the current stage. This would reduce dramatically the sizes of matrices whose pseudo-inverse matrices need to be calculated at each stage.

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Yuichi Ohsita received the M.E. and Ph.D. degrees in Information Science and Technology from Osaka University, Japan, in 2005 and 2008, respectively. He is now an Assistant Professor in the Graduate School of Economics at Osaka University. His research interests include traffic matrix estimation and countermeasure against DDoS attacks. He is a member of IEICE and ACM.

Takashi Miyamura received the B.S. and M.S. degrees from Osaka University, Osaka, Japan, in 1997 and 1999, respectively. In 1999, he joined NTT (Nippon Telegraph and Telephone Corp.) Network Service Systems Laboratories, where he was engaged in research and development of a high-speed IP switching router. He is now researching next-generation backbone network architecture and design. He received Paper Awards from the 7th Asia-Pacific Conference on Communications in 2001. He is a member of IEICE and the Operations Research Society of Japan.

Shin’ichi Arakawa received the M.E. and D.E. degrees in Informatics and Mathematical Science from Osaka University, Osaka, Japan, in 2000 and 2003, respectively. He is currently an Assistant Professor at the Graduate School of Information Science and Technology, Osaka University, Japan. His research work is in the area of photonic networks. He is a member of IEICE.

Shingo Ata received M.E. and Ph.D. degrees in Informatics and Mathematical Science from Osaka University in 1998 and 2000, respectively. He is an Associate Professor in Information and Communication Engineering at Osaka City University, Japan. His research works include networking architecture, design of communication protocols, and performance modeling on communication networks. He is a member of IEICE and ACM.

Eiji Oki is an Associate Professor of University of Electro-Communications, Tokyo Japan. He received B.E. and M.E. degrees in Instrumentation Engineering and a Ph.D. degree in Electrical Engineering from Keio University, Yokohama, Japan, in 1991, 1993, and 1999, respectively. In 1993, he joined Nippon Telegraph and Telephone Corporation's (NTT's) Communication Switching Laboratories, Tokyo Japan. He has been researching multimedia-communication network architectures based on ATM techniques, traffic-control methods, and high-speed switching systems. From 2000 to 2001, he was a Visiting Scholar at Polytechnic University, Brooklyn, New York, where he was involved in designing tera-bit switch/router systems. He was engaged in researching and developing high-speed optical IP backbone networks with NTT Laboratories. Dr. Oki was the recipient of the 1998 Switching System Research Award and the 1999 Excellent Paper Award presented by IEICE, and the 2001 Asia-Pacific Outstanding Young Researcher Award presented by IEEE Communications Society for his contribution to broadband network, ATM, and optical IP technologies. He co-authored two books, "Broadband Packet Switching Technologies," published by John Wiley, New York, in 2001 and "GMPLS Technologies," published by RC Press, Boca Raton, in 2005. He is an IEEE Senior Member.

Kohei Shiomoto is a Senior Research Engineer, Supervisor, Group Leader at NTT Network Service Systems Laboratories, Tokyo, Japan. He joined the Nippon Telegraph and Telephone Corporation (NTT), Tokyo, Japan in April 1989, where he was engaged in research and development of ATM traffic control and ATM switching system architecture design. From August 1996 to September 1997, he was engaged in research on high-speed networking as Visiting Scholar at Washington University in St. Louis, MO, USA. From September 1997 to June 2001, he was directing architecture design for high-speed IP/MPLS label switching router research project at NTT Network Service Systems Laboratories, Tokyo, Japan. From July 2001 to March 2004, he was engaged in the research fields of photonic IP router design, routing algorithm, and GMPLS routing and signaling standardization at NTT Network Innovation Laboratories. Since April 2004, he has been engaged in the research fields of photonic IP router design, routing algorithm, and GMPLS routing and signaling standardization at NTT Network Service Systems Laboratories. Since April 2006, he has been leading the IP Optical Networking Research Group in NTT Network Service Systems Laboratories. He is active in standardization of GMPLS in the IETF. He received the B.E., M.E., and Ph.D degrees in information and computer sciences from Osaka University, Osaka in 1987 1989, and 1998, respectively. He is a member of IEICE, IEEE, and ACM. He was a Secretary of International Relations of the Communications Society of IEICE from June 2003 to May 2005. He was the Vice Chair of Information Services of IEEE ComSoc Asia Pacific Board from January 2004 to December 2005. He was engaged in organization of several international conferences including HPSR 2002, WTC 2002, HPSR 2004, WTC 2004, MPLS 2004, iPOP 2005, MPLS 2005, WTC2006, iPOP 2006, and MPLS 2006. He received the Young Engineer Award from the IEICE in 1995. He received the Switching System Research Award from the IEICE in 1995 and 2001. He co-authored "GMPLS Technologies: Broadband Backbone Networks and Systems (Optical Engineering)" Marcel Dekker Inc.

Masayuki Murata received the M.E. and D.E. degrees in Information and Computer Sciences from Osaka University, Japan, in 1984 and 1988, respectively. In April 1984, he joined Tokyo Research Laboratory, IBM Japan, as a Researcher. From September 1987 to January 1989, he was an Assistant Professor with Computation Center, Osaka University. In February 1989, he moved to the Department of Information and Computer Sciences, Faculty of Engineering Science, Osaka University. From 1992 to 1999, he was an Associate Professor in the Graduate School of Engineering Science, Osaka University, and from April 1999, he has been a Professor of Osaka University. He moved to Graduate School of Information Science and Technology, Osaka University in April 2004. He has more than three hundred papers of international and domestic journals and conferences. His research interests include computer communication networks, performance modeling and evaluation. He is a fellow of IEICE and a member of ACM, The Internet Society and IPSJ.